



Less is Moore: Carbon Nanotube Transistors

That new, super-fast computer you bought six months ago is already outdated? That's Moore's law in action: the performance of computers doubles every 18 months. But more and more effort is required for that trend to continue; and eventually, it is predicted that fundamental limits on size reduction will hamper further improvement in device performance. That's where carbon nanotubes (NTs) come in. Discovered about 10 years ago, NTs are cylinders made entirely of carbon, with diameters of only a nanometer. Because the tubes are 100% carbon, they are very resistant and have exceptionally high strength. Furthermore, NTs have unusual electronic properties, as they can be either semiconducting or metallic. Such intriguing properties have excited a lot of interest in using NTs in electronic devices. Indeed, a number of groups have fabricated NT-based devices such as p-n junctions, Schottky diodes, field-emission displays and ultra-sensitive sensors. But probably the most intriguing device fabricated to date is a field-

effect transistor (FET) that uses a single NT to carry the current.

Figure 1 (a) shows an Atomic Force Microscope image of a NT-FET fabricated at IBM in 1998. The current flows between the electrodes through the NT; by changing the control voltage, one can change the current from high to low, giving rise to the "on" and "off" states of the device and hence the transistor action. But why does it work? To make a conventional silicon transistor, much effort goes into controlling dopant concentrations, doping profiles, properties of contacts, etc. In contrast, the device of Fig. 1 (a) was simply made by laying a NT across two electrodes, with absolutely no treatment or doping of the NT. So why should it work at all?

To address this issue, one needs to model the electronic transport properties of the NT-FET. The difficulty is that electronic transport through NTs does not follow the conventional models developed in the context of silicon devices. For example, electrons in

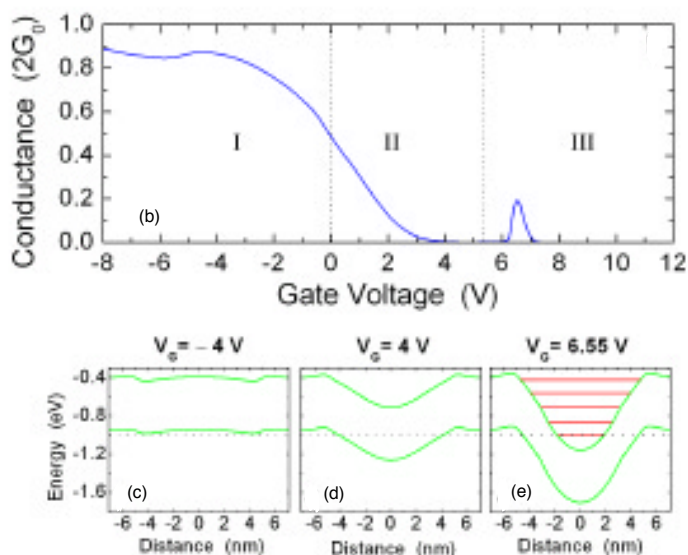
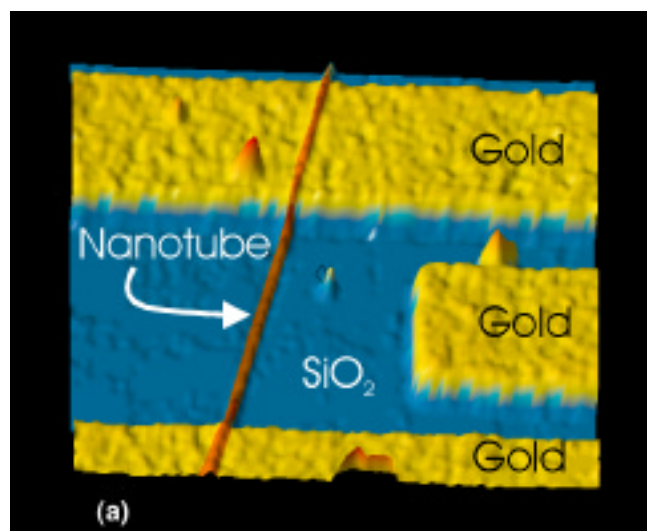


Figure 1. (a) AFM image of a carbon nanotube transistor (courtesy of R. Martel, IBM). (b) Calculated conductance of the NT-FET at low bias, as a function of gate voltage. (c – e) Valence and conduction band edges as a function of distance along the NT. The dotted line is the Fermi level. In (e), the horizontal lines represent the energy levels due to quantum confinement.



silicon undergo many collisions, but in a NT there are very few defects and the electrons move ballistically rather than diffusively. Furthermore, because of their small lateral dimension, NTs have quantized wavevectors perpendicular to the direction of current flow; no such effect exists in current silicon devices.

François Léonard, in collaboration with J. Tersoff, of the IBM T.J. Watson Research Center, calculated the current across the NT-FET using a quantum transport theory developed for NTs. *Figure 1 (b)* shows the calculated small bias conductance of the NT-FET. At large and negative gate voltages (region I) the conductance is high; as the gate voltage is increased to positive values the conductance drops dramatically, dropping to essentially zero in region II. These two regions correspond to the “on” and “off” states of the device, and one can switch between the two states by changing the gate voltage—the transistor action. A more detailed understanding of this effect is obtained by looking at band diagrams as in *Figures 1 (c)* and *1 (d)*. In region I, the valence and conduction bands are flat, and a carrier at the Fermi level can move across the NT without encountering any barriers, leading to a high conductance. In contrast, the bands in region II have a strong bend in the middle of the device, creating a barrier that blocks the NT, giving low conductance.

Although regions I and II explain the transistor action in the NT-FET, we have also discovered additional functionality in the same device. At higher gate voltages, the strong band-bending gives rise to a “quantum dot” in the middle of the device, *Fig. 1 (e)*. This creates discrete energy levels in the NT. As we change the gate voltage, these energy levels move in and out of the Fermi level, and electrons can tunnel through the quantum dot. This gives peaks in the conductance, the first of which is shown in region III



Figure 2. François Léonard earned a PhD in Physics from the University of Toronto, Canada. He joined Sandia as an LTE in 2000 and is currently an SMTS in the Thin Film and Interface Science department. His main research interests are in electronic transport in nanostructures and dynamics of self-assembly.

of *Fig. 1 (b)*. Hence, the NT-FET does double-duty: it acts as a regular transistor but also acts as a gated resonant tunneling device. This long-sought type of device has proven extremely difficult to fabricate with ordinary semiconductors, but comes “for free” with the tiny nanotube transistor.

Our results suggest that nanotubes are excellent candidates for future nanoscale devices. While their replacement of silicon is uncertain, one can say with certainty that nanotubes and other nanostructures will continue to amaze us with exciting new science.